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In-situ measurements and numerical modeling of railway traffic-induced ground vibrations in urban areas

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Abstract

Railway traffic-induced vibrations are becoming one of the major environmental concerns in urban areas. Such vibrations may affect the quality of life of people settled in the vicinity of railway lines with frequent traffic. This paper contains the results from the research conducted by in-situ measurements and numerical modelling of railway traffic-induced vibrations. First, the transducers and the acquisition system are described and the methodology for processing of the measured vibrations caused by motion of trains is discussed. Then, a proposed numerical model based on the finite element method (FEM) is explained. Numerical modelling of railway traffic-induced ground vibrations considers several mechanisms and a number of factors such as distance from the source, speed and type of traffic, quality of tracks, soil properties, properties of structures, etc. The proposed 3D FEM model for prediction of railway traffic-induced vibration is based on the elastic half-space theory. The soil's Young's modulus of elasticity and the Poisson's coefficient can be normally estimated from the longitudinal and shear wave velocities obtained by geophysical measurements. Soil layers of different properties can also be included in the model. The basic problem of FEM simulation is the calculation of the predominant period of the elastic half-space. The analyses have shown that the forced-vibration method provides a more realistic prediction of the predominant period compared to that of the ambient-vibration method. The results from the FEM analyses have also been confirmed by using the standard empirical geotechnical model. Apart from verification of the in-situ measurements, the proposed numerical model and analyses can serve as a tool in the practice of prediction of vibrations on a specific terrain. In such a way, possible measures for protection against vibrations can be undertaken. To illustrate the proposed methodology, site investigations and analyses carried out for the Kumanovo–Deljadrovce section are presented in the paper.

Key words: railway traffic-induced vibrations, in-situ measurements, forced-vibrations, ambient-vibrations, FEM

1 Introduction

Railway traffic-induced vibrations and noise in the vicinity of the residential areas are becoming one of the major environmental concerns nowadays. Although, vibration caused by passing trains is normally too weak to cause any possible damage to buildings, residents affected by vibration may experience annoyance that may affect the quality of their lives. However, recent experiences (Zagreb earthquake, March 2020) have shown that post-earthquake behaviour of buildings damaged by earthquake can be very sensitive to such vibrations. In normal conditions, the main sources of railway traffic-induced vibrations include train electric traction motors or electromagnets, control units and associated cooling fans; imperfections of wheel, rail running surfaces, etc. (see [1]). The vibration magnitude will depend on the distance from the source, speed and type of traffic, quality of tracks, properties of the soil transmission medium, properties of nearby structures, etc. Railway traffic-induced vibration is usually accompanied by ground-borne noise. The relative distinction between these two phenomena (vibration sensation and audible noise) can be done based on their frequency, sources of vibrations, properties of the transmission medium and its transmission mechanism to nearby structures as well as personal sensitivity. Generally, when the transmission medium consists of stiff soils (i.e., solid rock), the ground-borne noise is generally more important than the vibration and the dominant vibration frequencies are higher (i.e., around 50 Hz, see [2]). When the transmission medium is a soft soil (i.e., clay or peat), the vibration sensation may be more important than the ground-borne noise and the dominant vibration frequencies are lower (around 5 Hz, see [2]). In addition to soil properties, soil-structure interaction also plays one of the most important roles in the vibration propagation phenomenon, so that the proposed mitigation measures against the vibration sensation shall be based on these two factors. Here, we will only mention the phenomenon of airborne noise, i.e., noise transmitted from the wheels-track contact and from the train motors and equipment to nearby structures directly through the air. However, this type of audible vibrations has not been the subject of this research. The presented research has been focused on quantification of railway traffic-induced vibrations (sometimes referred as to as "ground-borne" vibration), rather than any type of noise. Ground-borne vibration (see Fig. 1) is generated by the interaction between the train and the tracks. Then, the induced waves propagate through the ground, reaching the foundation of nearby structures. The transmitted vibration may be observed as perceivable vibration of the floor, as shown in Fig. 1. Usually, ground-borne vibrations are associated with a frequency range between 1 and 100 Hz. Note that some regulative codes related to protection with needed measures for mitigation of this type of vibrations is defined in ISO 14837-1: Mechanical Vibration – Ground-Borne Noise and Vibration Arising from Rail Systems – Part 1, General Guidance (see [3]) and ISO 2631-2:2003: Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration – Part 2: Vibration in Buildings (1 Hz to 80 Hz), version 2008-10-23 (see [4]).

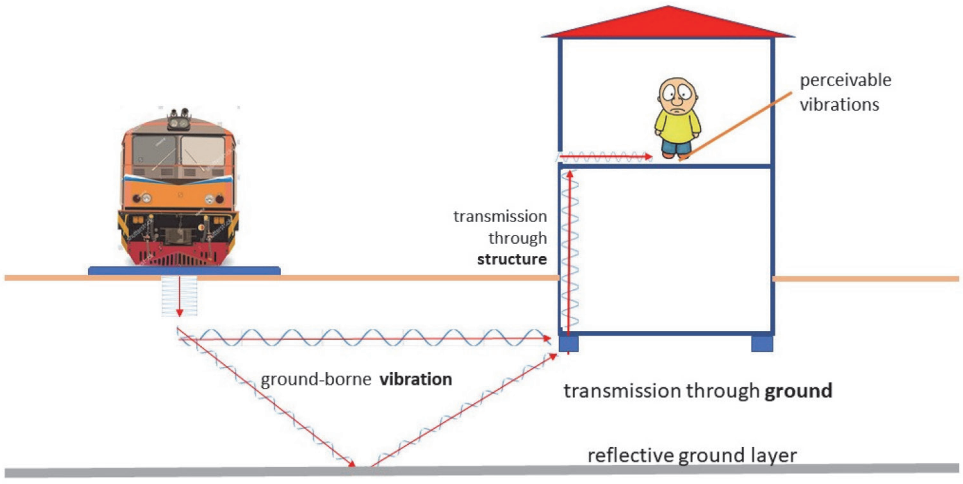

Figure 1. Ground-borne vibration due to railway-traffic transmitted to nearby structures

In this paper, a methodology for quantification of vibration level is proposed. The investigation involved in-situ measurements and Finite Element Method (FEM) numerical modelling and analysis. The numerical analyses have primarily been performed to verify the results from the measurements. However, the proposed numerical model can further serve as a tool in the practice of prediction of vibrations on a specific terrain. In such a way, possible measures for mitigation of the vibration effects can be undertaken. To illustrate the proposed methodology, site investigations and analyses carried out for the Kumanovo–Deljadrovce section are presented in the paper.
The results from the research are presented in several chapters. In Chapter 2, the methodology and the results from the in-situ measurements of ambient vibrations, hammer-induced vibrations and train-induced vibrations at a specified railway route cross-section are described. The results are presented in terms of acceleration time-histories. Then, in Chapter 3, numerical modeling is discussed and the results from the analysis of the predominant natural frequencies of the soil deposit are presented comparatively with the Fourier spectra obtained from the measurements. Finally, conclusions from the overall research are drawn and some ideas and directions for future work are discussed.

2 In-situ measurements

The proposed methodology includes site investigations and numerical modeling & analyses. It has been implemented for the Kumanovo–Deljadrovce section within the frames of the project for geophysical investigation soil properties and measurement of vibrations caused by passing trains (see [5]), for the mentioned section.
The site investigation included the following steps: 1. Identification of critical zones (hotspots) with field observation of all buildings near the line; 2. Geophysical measure-

ments at selected profiles of the critical zones by use of the "hammer blow" method and definition of attenuation curves (transfer functions) from the geophysical equipment (velocity measurement) including acceleration measurement by using accelerometers as additional equipment (see [6]). 3. Measurement of vibration intensity (in terms of velocity) due to passing trains at the selected profile and measurement of accelerations by use of accelerometers. 4. Construction of attenuation curves based on measured velocities and accelerations and making prognosis about the level of vibration of structures situated at hotspots. 5. Evaluation of necessary measures for vibration reduction.

2.1 Construction of seismic-geological profiles using geophysical tests

The hammer blow test procedure has been used to determine the wave-propagation properties of the soil media for the selected hotspots (see [5]). The purpose of this test is to generate a vibrational impulse that travels from a source (point of impact) to a receiver (object) in a way similar to the travel of train-induced vibrations. The values from the installed sensors (meters) have been recorded by a multi-channel acquisition system. At this particular profile, the transfer function (attenuation curve) has been obtained on the basis of the ground response to a hammer blow measured by 12 geophones placed at a distance of 5 m along the transverse profile with a length of 60 m. It has also been obtained in another way, by placement of accelerometers at five points, in three directions, at a distance of 10 meters, (note that the first point is located 5 meters away from the railway). The seismic-geological structure of the measured profile has been compiled by use of the geophones. By calculating the obtained velocity in acceleration, the accelerations at all 12 measuring points (geophones) have been obtained and thus the attenuation curve of the profile has been obtained.

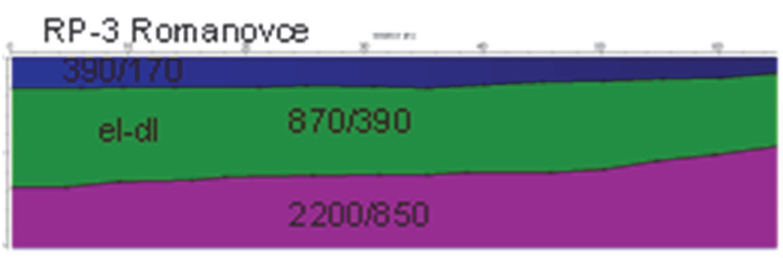

Figure 2. Results from the geophysical test for the selected soil profile RP-3 Romanovce

Using the hammer blow geophysical test, the propagation velocities of the seismic waves (longitudinal velocity V_p and transversal velocity V_s) for all seven profiles along the Kumanovo–Deljadrovce section have been estimated. Fig. 2 shows the seismic-geological distribution of the soil layers for the profile "RP-3 Romanovce" along with the obtained velocities V_p=390 m/s and V_s=170 m/s for layer 1 along depth from 0 to 2,0 m; V_p=870 m/s and V_s=390 m/s for layer 2 along depth from 2,0 to 11,0 m; and V_p=2200 m/s and V_s=850 m/s for layer 3 along depth from 11,0 to 20,0 m (see also Table 1 in the next section). These velocities have been used for identification of the soil layers' properties needed for the numerical FEM modelling and analysis. Layer no. 2, denoted as "el-dl" consists mostly of eluvial material combined with deluvial dusty clay deposit, while layer no. 3 denoted as "Pl" is mainly composed of sands, clays, and sandstones.

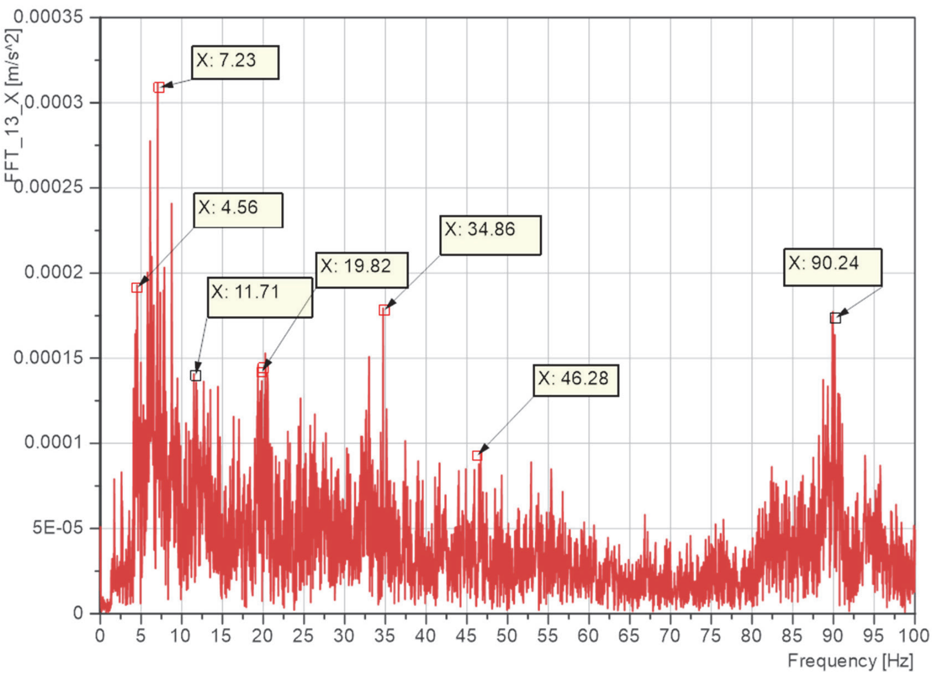

Figure 3. Fourier spectrum for the selected soil profile RP-3 Romanovce, x-direction

2.2 Additional in-situ measurements and results

In addition to the geophysical tests [5], new measurements have been conducted for profile "RP-3 Romanovce" (see [6]) for the same railway section. To perform the measurements, equipment with an acquisition system, basically consisting of seismic accelerometers that record vibrations, has been used. In this case, PCB Piezotronics devices, model 393B12, manufactured by National Instruments, with a sensitivity of 10,000 mV and a range of up to 4.9 m / sec2, i.e., 0.5g and NI 9234 cards have been used.

Two study cases have been investigated, i.e., cases with and without consideration of a nearby structure (a small house 11 m away from the railway). Five types of tests have been conducted – ambient vibration test, hammer blow test, passing of a passenger train, a freight train, and a locomotive. All measurements have been performed for 5 points on the soil surface (for the study case with a nearby house, three points have been located in the structure and two on the soil surface. The data analysis has been performed according to the ISO 2631-2 standard. Fig. 3 shows the obtained Fourier spectrum from the measurements of accelerations for the furthest point (no. 5) on the profile. It was the case without a nearby structure and for a freight train passage. These results have been selected as representative ones for comparison with the natural frequencies of vibrations of the soil deposit obtained from the numerical analysis (see the next chapter), since the influence of the excitation at point no.5 has been the least expressed. Also, in Fig.4, the measured level of vibrations in the nearby house is shown. The frequencies of vibration and their intensities have been compared to those in the provisions given in the ISO 2631-2 standard.

3 Numerical modelling and analysis

3.1 General

The ground vibration induced by moving trains represents a complex dynamic problem. According to Yang and Hung (see [7]), four major phases can be identified for the transmission of vibrations from a passing train through the railway and the subsoil media, up to the neighbouring structures: (a) Generation of vibration, (b) Transmission of vibration, (c) Reception, i.e., vibrations received by nearby buildings; and (d) Interception, i.e., reduction of vibrations through implementation of wave barriers, such as piles, trenches, isolation pads, etc. The integral problem considering all these four phases can be solved by using mainly four different approaches, i.e., analytical approaches, in-situ measurements, empirical prediction models and numerical simulation.

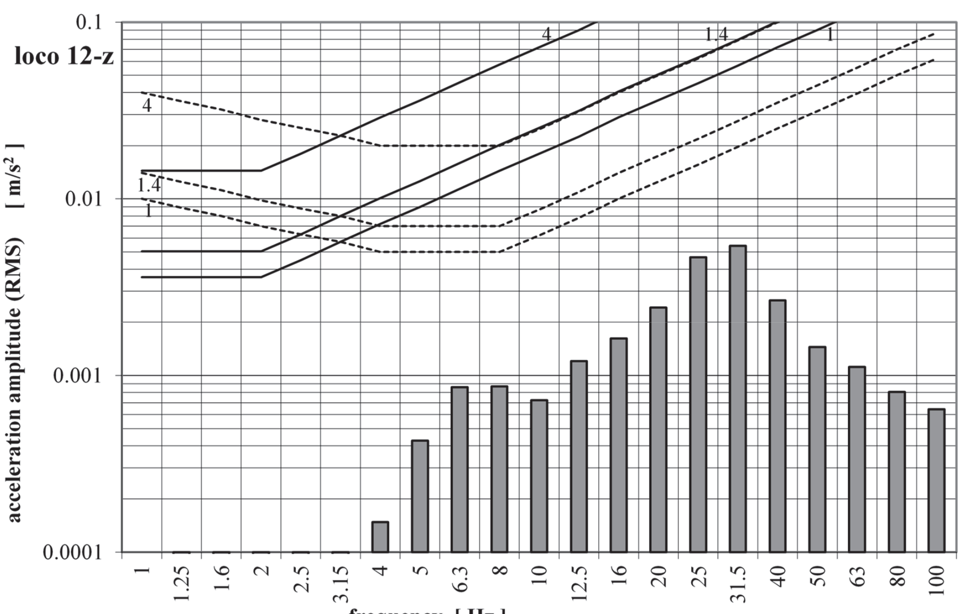

Figure 4. Measured level of vibrations in a nearby house in relation to the ISO 2631-2 standard

Analytical approaches have been used by many authors (for example, see [8]). In defining analytical relationships, they consider major factors affecting each problem, such as train speed, distance, soil conditions, etc. On the other hand, the conducting of a complete in-situ measurement of train-induced vibrations is always a costly and labor-intensive activity, Instead, empirical prediction models using attenuation curves (see [5]) can offer a practical approach to engineers. However, with the rapid advancement of the high-performance computer technology, numerical simulation appears as the most effective approach to modelling and solving wave propagation problems. In this research, supplementary to the empirical approach with the attenuation curves, the finite element method has been proposed for numerical prediction of vibration levels.

3.2 Generalized geotechnical model (2D GTM)

In this research, numerical modeling has been used for several reasons. First, it is important from the aspect of verification of the in-situ measurements and calibration of the model. Then, the proposed numerical model can be a useful tool for numerical prediction of the vibration levels of an affected structure. Presented in this paper is the verification of the FEM model along with discussion about the results from the measured natural frequencies of the soil deposit that have been compared to the numerically obtained ones. The analyses for calculation of the railway traffic-induced vibrations using the numerical model will be the subject of other papers. As mentioned before, the site investigations and analyses have been carried out for a profile section along the Kumanovo–Deljadrovce section route.

The dynamic properties of the soil medium play the most important role in the vibration transmission to nearby structures. However, they depend on many factors, like geological composition, number of layers, their spatial distribution, layers' depth (H_i) and thickness (h_i), then, layers' material properties as unit density (r_i), Jung's modulus of elasticity (E_i), shear modulus (G_i), Poisson's coefficient (m_i), angle of internal friction, cohesion of the material, etc. In Fig. 5, a generalized geotechnical model (see [11]) with denoted basic parameters for all soil layers is shown. The velocities of propagation of longitudinal (V_p) and transversal (V_s) seismic waves can be expressed as functions of the material properties of the actual soil layer, i.e., the Jung's modulus of elasticity, shear modulus, density (r) and Poisson's coefficient, as follows:

$$V_p = \sqrt{\frac{E\left(1-\mu\right)}{\rho\left(1+\mu\right)\left(1-2\mu\right)}} \tag{1}$$

$$V_s = \sqrt{\frac{G}{\rho}} \tag{2}$$

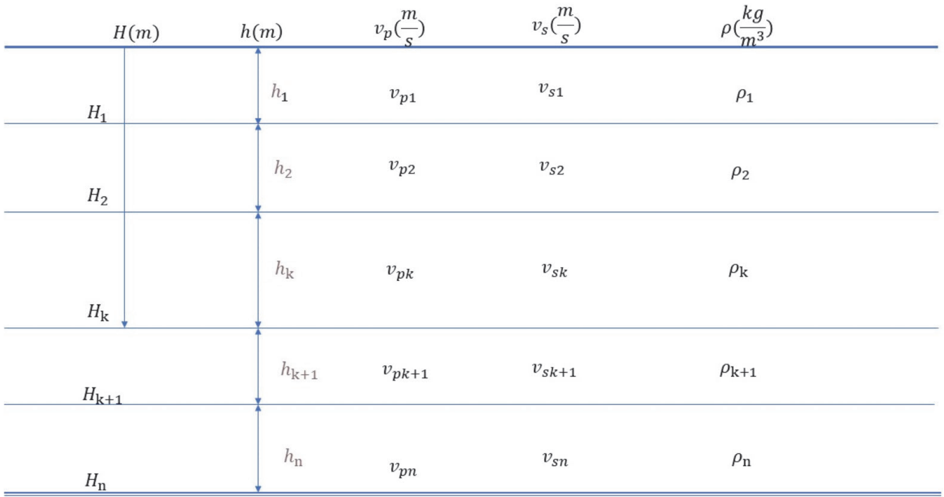

Figure 5. Generalized geotechnical model with basic parameters for all soil layers.

Table 1. Properties of the soil layers

	Layer 1: H=0,0 – 2,0 m	Layer 2: H=2,0 – 11,0 m	Layer 3: H=11,0 – 20,0 m
V_p [m/s]	390	870	2200
V_p [m/s]	170	390	850
r [t/m^3]	1,0	1,1	1,2
h [m]	2,0	9,0	9,0
m	0.383	0.374	0,412
E [kPa]	79921	459853	2448867

However, if the velocities of the transversal seismic waves for all soil layers are known from geophysical measurements, we can calculate the predominant period of vibration T_0 for the soil profile using the following well-known relationships (see [9]):

$$T_0 = \frac{4H}{\overline{V_s}} \text{ [s]} \tag{3}$$

where:

$$H = \sum_{i=1}^{n} h_i \text{ [m]} \tag{4}$$

$$\overline{V_s} = \frac{\sum_{i=1}^{n} V_{si} h_i}{\sum_{i=1}^{n} h_i} \text{ [m/s]} \tag{5}$$

The period of vibrations T_m for some higher mode m can be obtained using the following relationship:

$$T_m = \frac{4H}{(2m-1)\overline{V_s}} \tag{6}$$

where m is the mode number to be calculated. Using equations (1) to (6) and considering the measured transversal velocities V_S for each soil layer from the geophysical test, the natural periods of vibrations have been obtained (see Table 2). In Table 1, the properties of the soil layers are presented.

3.3 Finite element modelling (3D FEM)

To perform FEM numerical modeling and analysis, we need the parameters *E*, *G*, *m* and *r* for all soil layers. Shear modulus *G* can be obtained by using the elasticity theory, and *E* and *m* can be calculated from the system of equations (1) and (2). Thus, the following expressions can be obtained:

$$G = \frac{E}{2(1+2\mu)} \tag{7}$$

$$\mu = \frac{2V_s^2 - V_p^2}{2(V_s^2 - V_p^2)} \tag{8}$$

$$E = 2V_s^2 \rho (1+\mu) \tag{9}$$

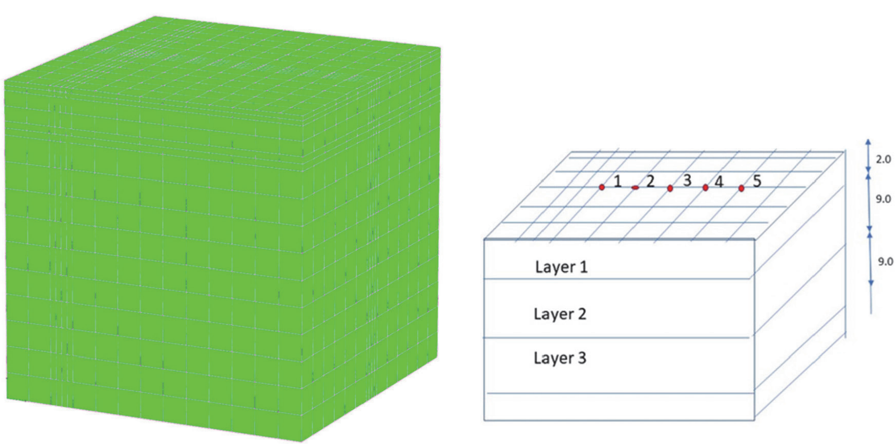

Figure 6. 3D Finite element model of the analysed soil deposit (left) with denoted measurement points (right). Note that the point no. 1 is nearest to the railway (5 m away), and the spacing between the points is 10 m

Parameter *r* is usually obtained by laboratory tests based on in-situ taken soil specimen. However, in our case, such investigation has not been performed, so that the unit density of the soil layers has been assumed based on empirical tables that include soil classification. The calculated soil parameters, i.e., Jung's modulus of elasticity (E_i), shear modulus (G_i), Poisson's coefficient (m_i), for all three soil layers, using the equations from (7) to (9), are presented in Table 1.
A 3D FEM model of the soil profile has been generated. The model grasps a part of the analyzed soil deposit in the form of a cube proportioned 65x65x65 m in length, width, and depth (see Fig. 6). Since a sufficient depth has been grasped with the model (65 meters of depth), the boundary conditions on the bottom surface have been prescribed zero displacements along all three axes. The boundary conditions on the four vertical surfaces have been modelled by additional link elements having appropriate spring stiffness coefficients calibrated so that the model has been able to simulate the frequency values obtained by the 2D Generalized Geotechnical Model (2D GTM), discussed previously. The top surface has been modelled by free boundary conditions related to displacements. The solution with infinite elements could also be the solution to this problem (see [7]), as an alternative to this model. However, the infinite elements solution will be considered in future works. In Table 2, a comparison of the natural frequencies obtained by the 2D General Geotechnical Model (2D GTM) and the 3D FEM numerical model with the resonant frequencies measured in-situ for the freight train passage, are given.

Table 2. Comparison of resonant frequencies in [Hz], obtained by using General geotechnical model (2D GTM), the 3D FEM model and in-situ tests

Mode	2D GTM	3D FEM	Test
1	7,188	7,427 (Y)	7,23 (X)
2	21,563	19,25 (X)	19,82 (X)
3	35,938		34,86 (X)
4	50,313		46,28 (X)
5	64,688		
6	79,063		82,45 (Y)
7	93,438		95,01 (Y)

4 Conclusions

From the described investigation, it can be concluded that the problem of railway traffic-induced vibration perceived by people living in buildings adjacent to railways is becoming increasingly topical. It is not only related to the structural serviceability period during which residents are affected by annoying vibrations, but it also appears to be topical for buildings located near stations damaged by earthquakes (for example, the Zagreb earthquake 2020) whose post-earthquake behaviour may be affected by tramway/

train induced vibrations. For both cases, in-situ measurements and construction of attenuation curves are still standard approaches, however, they should be supplemented by contemporary numerical FEM modelling for prediction of the vibration intensity level in order to anticipate appropriate mitigation measures. For the post-earthquake case, to avoid the risk of damage propagation, additional measurements and inspection of damaged buildings should be performed and, if needed, tramway/train traffic reduction should be proposed during the first mitigation period.

References

[1] Thompson, D. (2009): *Railway Noise and Vibration, Mechanisms, Modelling and Means of Control*. Elsevier, Amsterdam, The Netherlands.

[2] UIC (2017): Railway Induced Vibration - State of the Art Report, International Union of Railways (UIC) - Paris, 2017

[3] ISO 14837-1 (2005): Mechanical Vibration – Ground-Borne Noise and Vibration Arising from Rail Systems – Part 1: General Guidance.

[4] ISO 2631-2:2003 (2008): Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration – Part 2: Vibration in Buildings (1 Hz to 80 Hz), version 2008-10-23

[5] TEUOPRD (2014): Preparation of Project and Design Documentation for the Railway Sections Along the Corridor X Including Branch Xd, *Ref. No. EuropeAid/130167/D/SER/MK, January 2014*, Vibration Impact study, Section Kumanovo- Deljadrovci, Variant 120 km/h, DEKONS EMA.

[6] Naumovski, N. (2021): Integrated Metodological Approach to Analysis of Railway Traffic Vibration Impact on People and Facilities. Ph.D. thesis (in preparation), UKIM-IZIIS, Skopje.

[7] Yang, Y.B., Hung, H.H. (2009): *Wave Propagation for Train-Induced Vibrations, A Finite/Infinite Element Approach*. World Scientific Publiching Co. Pte. Ltd., London.

[8] Ferrara, R. (2013): A Numerical Model to Predict Train Induced Vibrations and Dynamic Overloads. Ph.D. thesis, University of Reggio, Calabria.

[9] Stojkovic, M. B. (2017): *Characteristics of Microtremors and Geotechnical Modelling of the Local Soil Structure*. UKIM-IZIIS, Skopje.